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Performance tests on a selection of 100-element charge-coupled devices

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PERFORMANCE TESTS ON A SELECTION OF 100-ELEMENT CHARGE-COUPLED DEVICES

G.M. Le Couteur, B.Sc.

Summary

A number of samples of a 100 element charge coupled device were supplied for appraisal and were tested under conditions relevant to the potential use of CCD's for solid stage image-sensing, storage, and signal processing at video frequencies. Although the particular devices tested had no foreseeable practical application in these areas, the information gained should be useful to the manufacturers in clarifying how this technology will need to be developed in order to produce products of real value to the broadcaster in the future.*

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* By the makers, GEC Hirst Research Centre, Wembley.

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August 1976
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PERFORMANCE TESTS ON A SELECTION OF 100-ELEMENT CHARGE-COUPLED DEVICES

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PERFORMANCE TESTS ON A SELECTION OF 100-ELEMENT CHARGE-COUPLED DEVICES

G.M. Le Couteur, B.Sc.

1. Introduction

The charge-coupled device is simple in basic concept and potentially offers a very high information packing-density at very low cost. Among the future applications in broadcast engineering are:

(1) Solid-state image-sensors as a replacement for television camera tubes.

(2) Solid-state image-sensors to replace the flying-spot tubes and photo-multipliers in telecines.

(3) Analogue and digital shift registers with, typically, hundreds of thousands of elements per chip.

(4) Analogue signal processors in the form of transversal filters.

The tests carried out on the samples supplied for assessment were aimed at exploring such defects as transfer inefficiency, dark-current variations, element-to-element sensitivity variation etc; where relevant, these characteristics were assessed as functions of clocking frequency.

It is not within the scope of this report to present a comprehensive theoretical description of how CCD's work, since although this is a relatively new technology, much information has already been documented elsewhere.[1] However, the devices used in these tests will be described in sufficient detail to enable the reader to grasp the essential principles of CCD operation.

2. Description of the CCD's tested

In CCD's information is carried as a series of 'packets' of electric charge. In general the amount of charge in each packet is proportional to the signal being transmitted. (For binary digital operation, therefore, the packets would be considered either empty or full).

The device consists of a silicon chip on the surface of which electrodes have been deposited with a very thin insulating layer of silicon oxide to isolate the electrodes from the silicon. The type of CCD with which we are concerned is the three-phase type, and this is illustrated in Fig. 1. It will be seen that every third electrode is connected to a common clock line, and that three clock lines are used to drive the device.

Each electrode is in effect a capacitor plate, the other common electrode being the silicon, and if (with P type silicon) a positive voltage is applied to an electrode, a region of carrier depletion will form under it due to the effect of the electric field. This is shown by the dotted profile. If negatively charged minority carriers (electrons) are then introduced into the depletion region, they will accumulate near to the surface of the silicon substrate, being drawn towards the positive electrode by the direction of the field. In a three-phase CCD, individual packets of charge are contained under every third electrode, and transfer of charge takes place as follows:

Fig. 1(a) All the charges are under the ϕ_2 electrodes, which are at a high potential (V_H). whilst ϕ_1 and ϕ_3 electrodes are at a low potential (V_L).

Fig. 1(b) The potential of the ϕ_3 electrodes is changed rapidly to V_H and the potential of the ϕ_2 electrodes changes slowly to V_L. This results in a potential gradient which draws the carriers across the inter-electrode gap from the ϕ_2 electrodes to the ϕ_3 electrodes.

Fig. 1(c) The ϕ_2 electrodes have reached potential V_L and the charge now rests under the ϕ_3 electrodes. The slow change of the ϕ_2 electrodes from V_H to V_L is essential, too rapid a change results in the carriers being forced into the substrate.

Fig. 1(d) This shows the ϕ_1, ϕ_2 and ϕ_3 waveforms necessary to provide continuous transfer of charge packets along the device. The decay time of each trailing edge is usually not critical provided that it is not too short. This can, however, become a limiting factor in determining the maximum speed of operation of the device, since the duration of the trailing edge is closely linked with the charge transfer time at high clocking speeds.

It is possible to introduce the charge packets either by injecting charge into the substrate through a diode at the input end of the array, thus using it as a shift register or, in the image-sensing mode, by the action of light on the silicon chip; the photons generate hole-electron pairs, the electrons remaining under the charged electrodes. The charge packets are extracted by means of a diode at the output of the array. In the imaging devices considered here, the hole-electron pairs are not generated directly under the transfer electrodes. A separate image-sensing area is used which lies alongside the transfer register, and charge developed there is transferred laterally into the transfer register through a so-called transfer gate, shown in Fig. 2, which illustrates the structure of the CCD as seen from above. The electrodes which form the image-sensing area are made of transparent polysilicon which is a sufficiently good electrical conductor for the purpose, whilst retaining reasonably good light transparency.

Fig. 3 shows all the waveforms needed to drive the

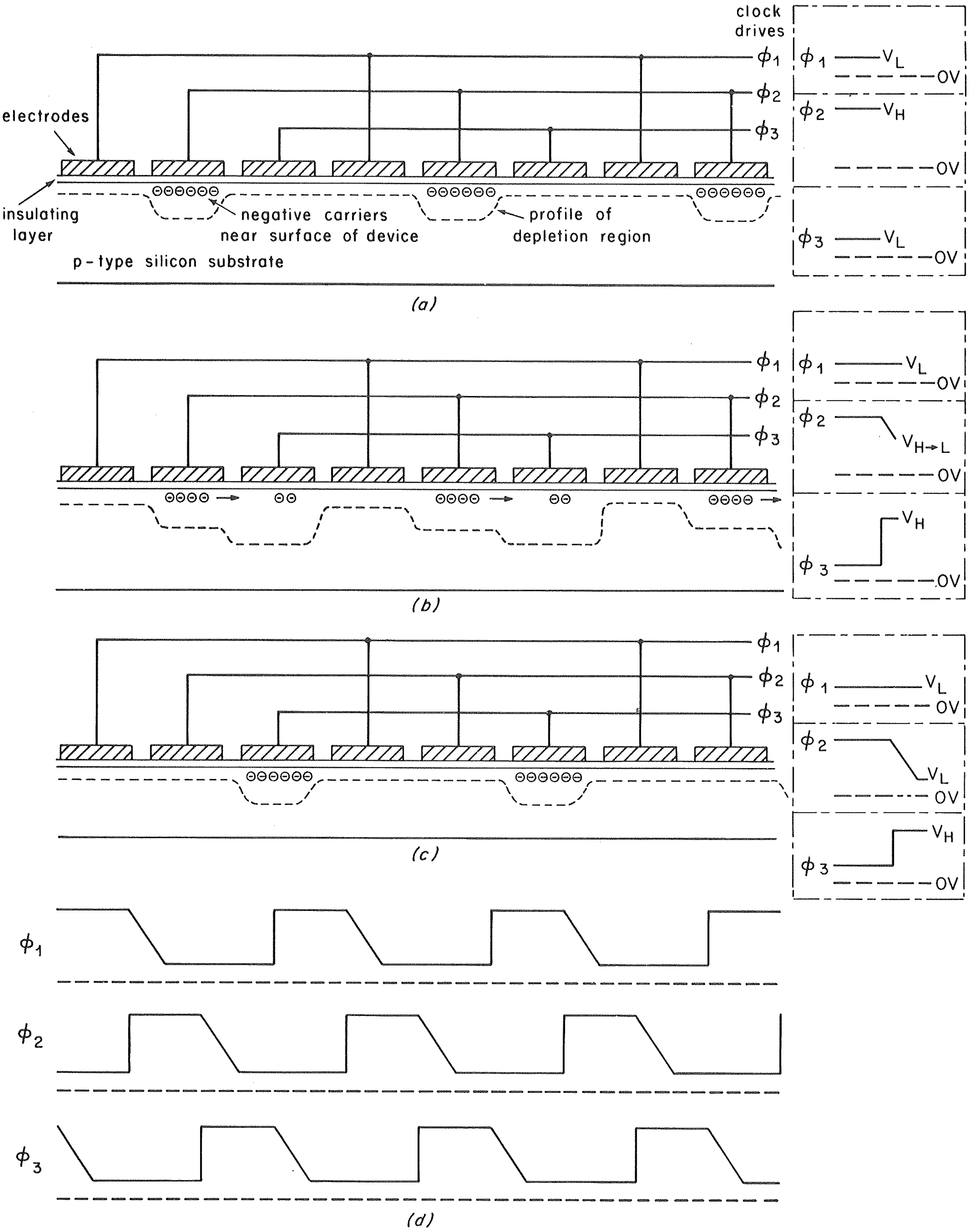

Fig. 1 - Charge transfer in a 3 phase CCD

1(a) Phase 1 (1b) Phase 2 1(c) Phase 3 1(d) Idealised 3 phase waveforms

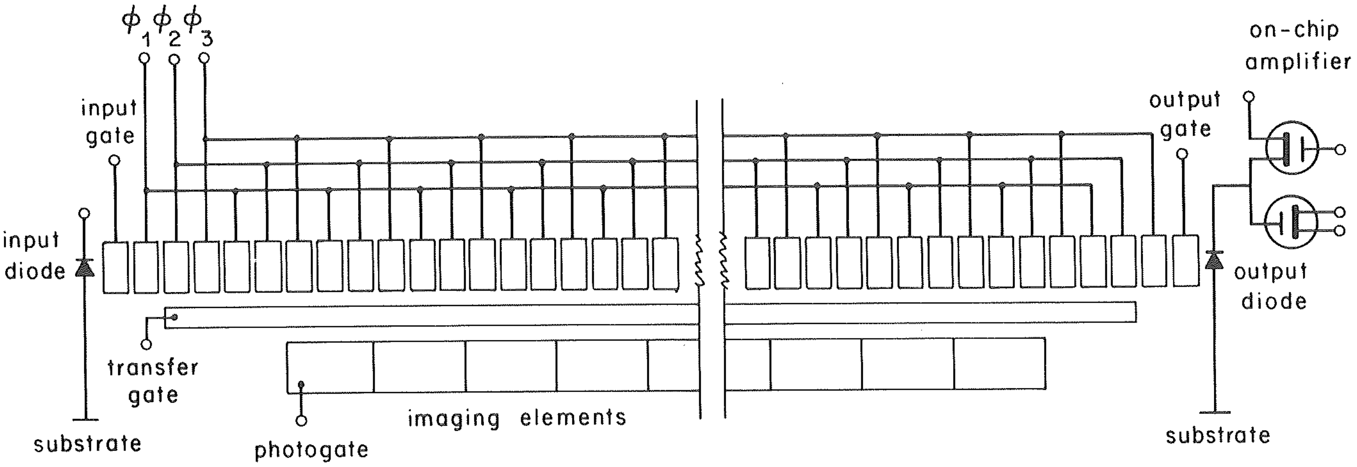

Fig. 2 - Functional layout of the 3 phase CCD's tested

device, and Fig. 4 is a cross section through the chip along the line of the photogate, transfer gate and ϕ_1 electrodes. The particular instants represented by Fig. 4(a), (b), (c), and (d) are indicated on Fig. 3. The sequence of operations for the transfer of charge from the image-sensing region to the shift-register region is as follows:

Fig. 4(a) The photogate is at level V_H during the whole integration period, the transfer gate is closed (V_L), and charge is being shifted under the three phase shift-register electrodes, the direction of transfer being perpendicular to the diagram.

Fig. 4(b) Charge transfer ceases under ϕ_1, and the transfer gate opens. The photogate begins to close slowly, thus shifting the charge to the transfer gate and ϕ_1 electrodes.

Fig. 4(c) The photogate has closed (V_L) and light integration ceases. The transfer gate is slowly closing, and the charge is being transferred to the ϕ_1 electrodes.

Fig. 4(d) The photogate opens (V_H) and light integration recommences. The transfer gate is closed (V_L). All the new packets of charge are under

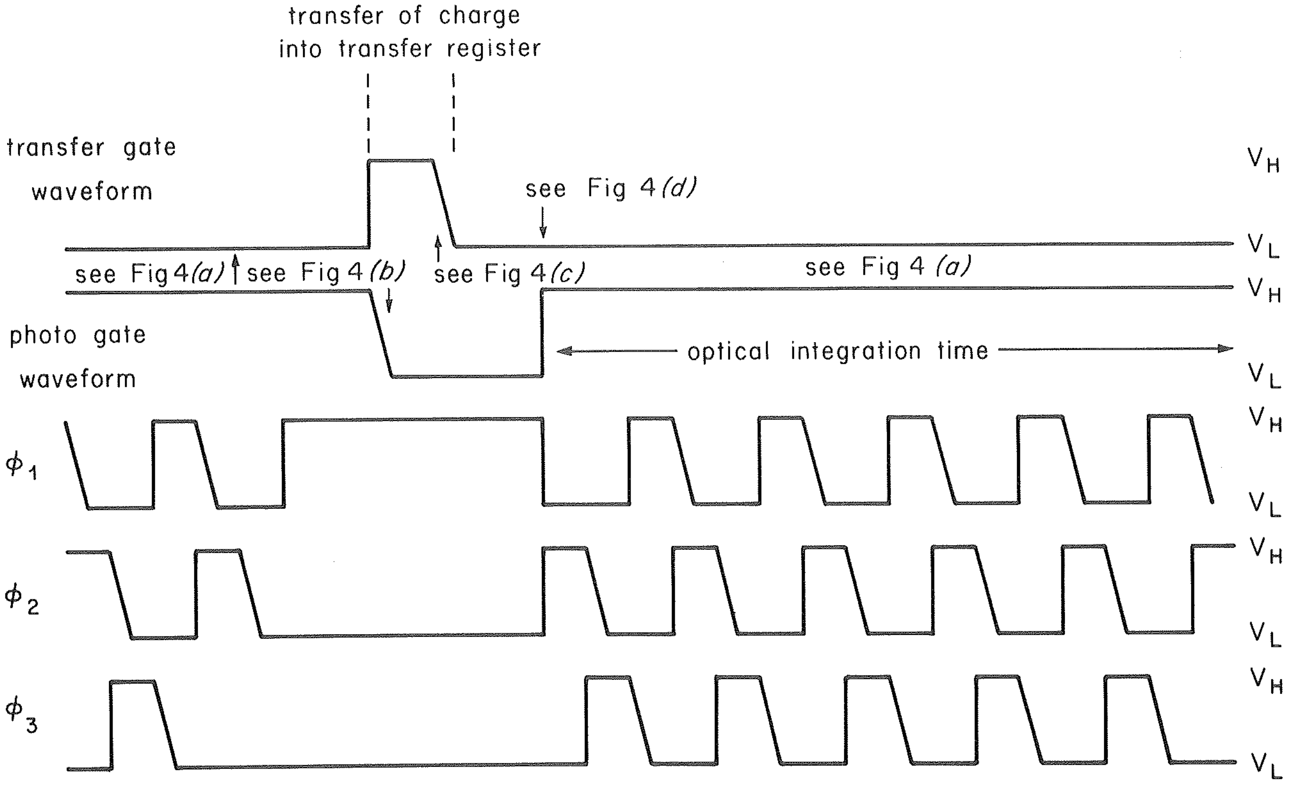

Fig. 3 - Waveforms required to achieve transfer of charge from the light sensitive area to the transfer area of the CCD

the ϕ_1 electrodes, and about to commence transfer down the shift-register.

This organisation of the device into separate image-sensing and transfer regions exists to prevent image smearing, which can arise if light integration occurs during charge transfer; this effect can occur when both imaging and charge transfer are combined under the same set of electrodes.

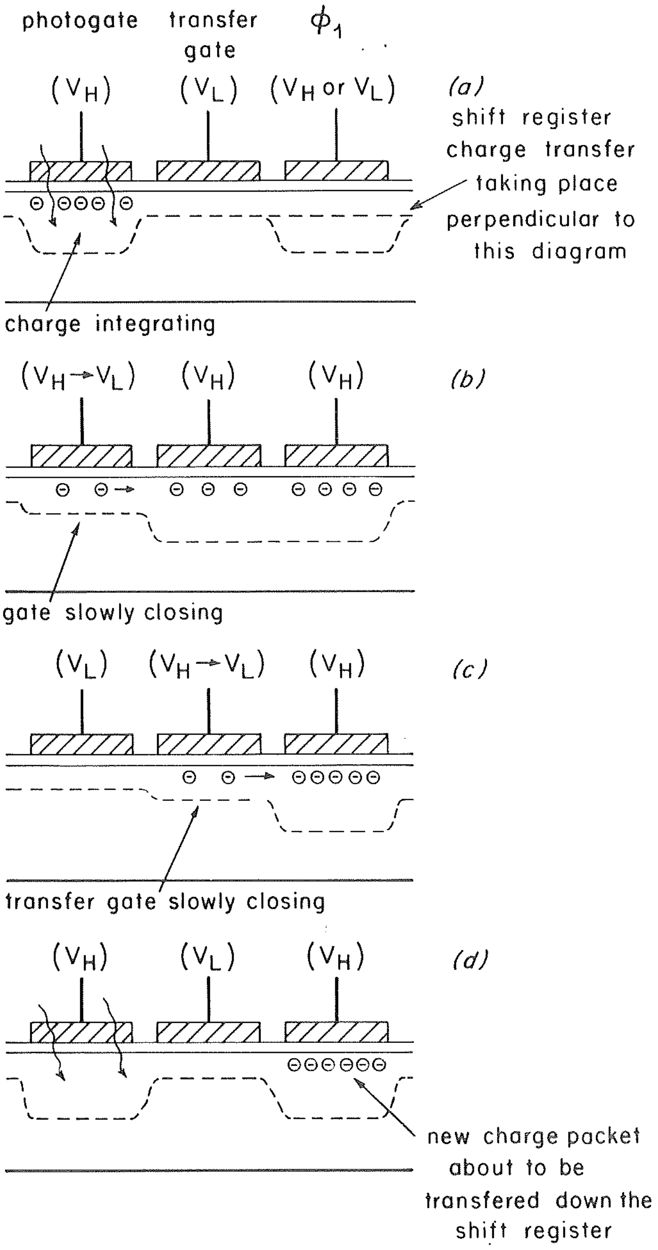

Fig. 4 - Charge transfer from the light sensitive area to the transfer area of the CCD

4(a) Charge integrating during light exposure
4(b) Photogate closing
4(c) Transfer gate closing
4(d) Transfer complete

3. Description and discussion of factors limiting the performance of CCD's

3.1. Clocking speed, transfer efficiency, charge bias

The maximum speed with which a CCD can be clocked is limited by the transit time of the carriers from one electrode to the next. If any attempt is made to move the carriers faster than this, a significant proportion of the charge will, in general, be left behind at each transfer, and the information will become smeared along the line of the transfer. The proportion of charge left behind each time is called the transfer inefficiency and is denoted by the symbol ϵ. The transfer efficiency, η, is defined as the proportion of the charge which shifts successfully at each transfer. It follows that $\epsilon + \eta = 1$, provided that there is no loss of total charge in the process.

Although transfer efficiencies in general are very high, typically 0·999 in a three-phase surface-channel CCD, there may be many hundreds of charge transfers involved and the effect of transfer inefficiency will be cumulative. Thus for example in a 100 element CCD there are 300 transfer electrodes; with $\eta = 0{\cdot}999$ the overall charge transfer will be $(0{\cdot}999)^{300} = 0{\cdot}740$, a significant charge loss.

Mathematical models have been evolved to explain the distribution of charge along CCD's as a function of transfer efficiency. Some of them take into account the fact that transfer efficiency is not strictly a constant but is to some extent signal level dependent.[2] For the purpose of this report, however, it is sufficient to use a fairly simple model which describes the distribution of charge along a three phase CCD, and assumes a constant transfer efficiency.[1]

Let

1 element = 1 triplet of CCD electrodes. (For a three-phase device).

η = transfer efficiency per electrode transfer.

ϵ = transfer inefficiency per electrode transfer.

N= number of element transfers taking place.

$$= \frac{\text{number of electrode transfers}}{3}$$

in a three-phase CCD.

Q_o = single packet of charge injected into the CCD.

Q_i = the charge appearing in element i after N transfers.

It can be shown that:-

$$Q_i \approx Q_o \frac{N!}{(N-i)!\,i!} (3\epsilon)^{N-i} (1-3\epsilon)^{i} \qquad (1)$$

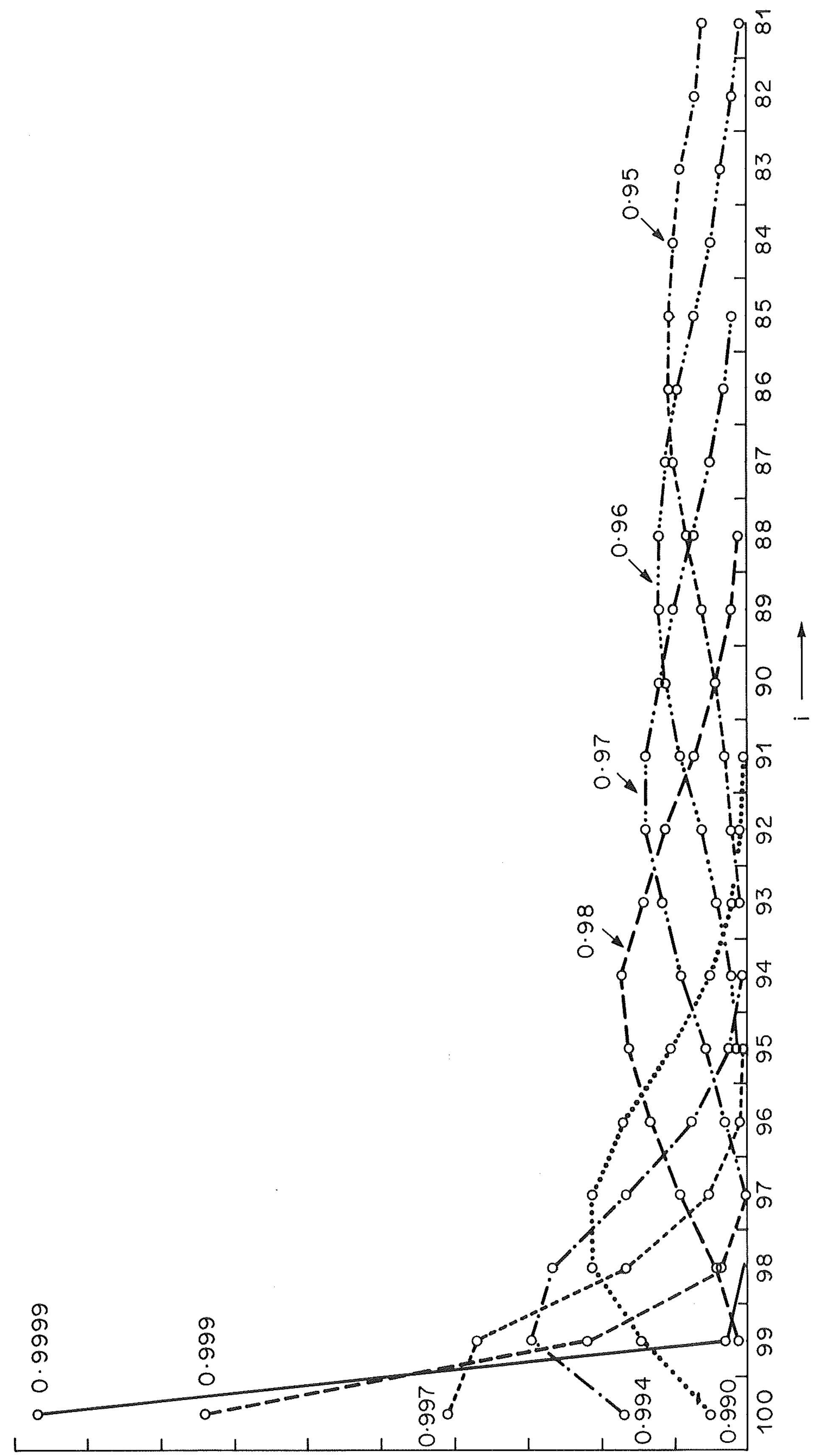

Fig. 5 - Relative charge distribution between elements 81 and 100 for various values of transfer efficiency

It should be noted that for large transfer inefficiencies, in particular when $\epsilon \rightarrow {}^1/3$, this expression reduces to the gaussian distribution

$$Q_i \approx Q_o \frac{Ni}{(N-i)\,!\,i\,!}$$

Equation (1) can be plotted as a series of points showing the charge packet distribution along the array for a range of values of transfer efficiencies. This is illustrated in Fig. 5 for the 100 element device being considered. The families of points so obtained clearly show how the distribution of charge is affected by the transfer efficiency. They show, that for high transfer efficiencies the bulk of charge is carried in the leading charge packet, but that as the transfer efficiency reduces, the bulk of the charge tends to lag behind the leading charge packet and the charge distribution approximates more closely to gaussian. It can be shown that in general the peak in the charge distribution is shifted back by one element every ${}^1/3\epsilon$ transfers.

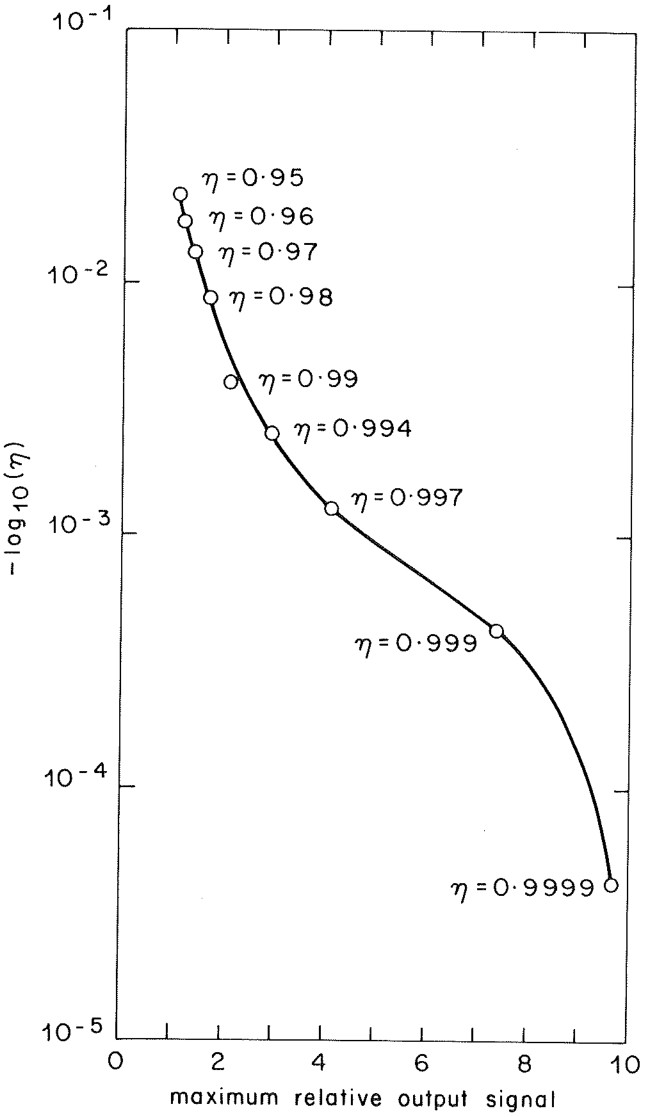

Fig. 6 - $Log_{10}(\eta)$ as a function of the maximum relative output signal

It is possible to determine the transfer efficiency by observing the charge packet distribution and then matching to the theoretical values shown in Fig. 5. It is more convenient however, to plot transfer efficiency as a function of the normalised theoretical maximum of the charge distribution, and thus read off the transfer efficiency directly from a measurement of the relative output pulse level. Such a curve is plotted in Fig. 6. Since the transfer efficiencies of interest are close to 1·0000, the values of $\mathrm{Log}_{10}\eta$ are plotted on a logarithmic scale to give a spacing equivalent to Log ($\mathrm{Log}_{10}\eta$).

Transfer inefficiency also has an effect on sinusoidal signals propagated through the device. Clearly, it must cause a reduction in amplitude as a function of the frequency of the sine wave. It can be shown that the sine wave amplitude emerging from the CCD is described by the expression

$$A_o = A_i \,\mathrm{Exp}\,(-\,n\epsilon\;[\,1 - \mathrm{Cos}\;2\pi f/f_c\,]\,) \qquad (2)$$

where A_i = Amplitude of input sine wave

A_o = Amplitude of output sine wave

f = frequency of sine wave

f_c = clock frequency of CCD

n = number of electrode transfers

If observations can be made of the amplitude of the output sine waves, expression (2) can be used to provide a further means of measuring transfer efficiency.

The maximum clocking rate for the devices under test was tentatively set by the manufacturers at no greater than 2 MHz for normal operation; the increase in transfer inefficiency being very rapid at higher frequencies. It is, however, known that the speed at which surface channel CCD's can operate is limited mainly by surface trapping states, and that the introduction of a charge bias* can considerably improve this performance. This is illustrated by Fig. 7.

In a surface channel CCD, the carriers are found near to the surface of the substrate, as shown in Fig. 7(a). In the manufacture of CCD's however, it has so far proved impossible to avoid the production of surface trapping states at the surface of the silicon; these, in effect, capture the carriers and hold them for a while before releasing them again. As a result a 'drag' is imposed on the carriers analogous in some ways to viscosity in liquids, which makes the average speed of the carriers near to the surface much less than those deeper in the substrate, this is illustrated in Fig. 7(b).

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* Also referred to as 'Fat Zero' in CCD literature

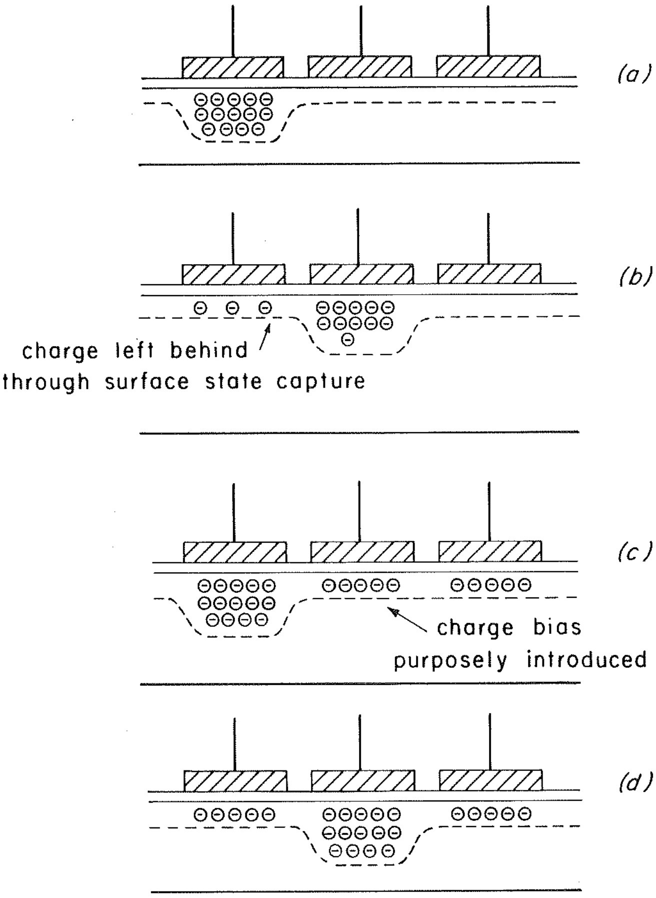
(a)
(b)
charge left behind through surface state capture
(c)
charge bias purposely introduced
(d)

Fig. 7 - The effect of charge bias on transfer efficiency

7(a) No charge bias, packet of charge about to be transferred

7(b) No charge bias, packet of charge imperfectly transferred due to transfer inefficiency

7(c) With charge bias, packet of charge about to be transferred

7(d) With charge bias, packet of charge transferred with high transfer efficiency

An effective improvement in performance can be realised by the introduction of a fixed amount of charge which continually occupies all the surface trapping states, (Fig. 9(c)). Any additional charge (the required signal) can then travel unimpeded, Fig. 7(d).

The main disadvantage of this approach is that the effective charge handling capacity is reduced. Nevertheless the increase in clocking speed by a factor of roughly five so obtained is worthwhile in many applications. Relevant experimental results will be found in section 4.1.1.

3.2. Blooming

Highlights can cause local over-exposure. In CCD image sensors this effect can be particularly objectionable since charge carriers generated in highly illuminated areas tend to spill over into adjacent areas, and the effect shown in the photograph Fig. 8 is produced. There are techniques available in the design and manufacture of CCD's which can help to prevent this, and clearly it would be necessary for any CCD sensor intended for broadcast application to be protected against blooming. However, the devices which form the subject of this report were not protected and blooming was frequently visible.

3.3. Linearity

Inherently, CCD sensors should have a linear relationship between light exposure and the corresponding charge developed in the substrate. In order to determine whether operating conditions could be found in which non-linearity was observable, it was decided to measure the linearity. The results are presented in section 4.2.

3.4. Sensitivity variations

All solid-state image sensors show variations in sensitivity between adjacent light-sensitive elements. Such variations are typically within the range ± 7%. With linear arrays, used for television line scanning, the subjective effect can be particularly objectionable since it appears in the resulting picture as a coherent vertical pattern present on every line. The fact that such variations exist also implies that, for colour operation where three devices are in use simultaneously, differences in sensitivity would show up as vertically coherent colour errors. Whilst it is possible

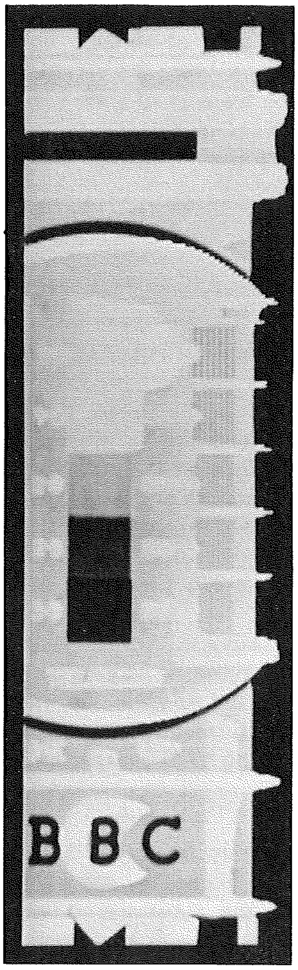

Fig. 8 - Photograph illustrating blooming

in principle, to apply electronic correction to compensate for this type of impairment the success of such correction techniques depends upon the extent to which the device is linear, and is more likely to be successful if the sensitivity variations are small.

3.5. Dark current

In the absence of illumination, CCD sensors develop observable charge due to thermal generation in the substrate. This charge, which gives rise to dark current, accumulates over the integration time of the device and, in low light applications, may be very significant, thus restricting the available dynamic range.

As might be expected from its thermal origins, the effect increases rapidly with temperature (roughly by a factor of 10 for every 20°C). There is therefore potentially a very great advantage to be gained by cooling the device during use. On-chip cooling using the Peltier effect is thought to be feasible, but as far as is known, this has not yet been demonstrated.

3.6. Dark current variations

Dark current of a uniform nature is undesirable in a light sensor; dark current variations are, however, usually also present, and can pose an even worse problem owing to the creation of a background pattern. In CCD area arrays these usually result in white dots of variable intensity randomly distributed over the picture; the variations are also temperature sensitive. The presence of these blemishes on the picture presents a problem for the broadcaster and it may be necessary to use electronic correction techniques involving storage.

3.7. Spectral response

The spectral response is of very great importance when considering the potential applications of CCD sensors in colour TV systems. Silicon devices inherently have a spectral response characteristic as illustrated by Fig. 9 which is a typical characteristic for a silicon diode vidicon-type tube, (for reference the unity quantum efficiency line is also shown), and CCD sensors generally seem to suffer an additional loss of sensitivity to blue light due to the poor blue transmittance of polysilicon. The multilayer manufacturing process can also result in interference effects giving rise to fine variations imposed upon the intrinsic spectral response. The existence of this fine structure could make it very difficult to maintain consistency between the spectral responses of nominally identical devices and could lead to serious colorimetric problems when using CCD sensors in colour systems.

These problems could largely be solved if it were possible to thin the slice of silicon to approximately 20 μm, and image through the substrate. Work is proceeding in this field and results seem to indicate that this does improve the blue response.

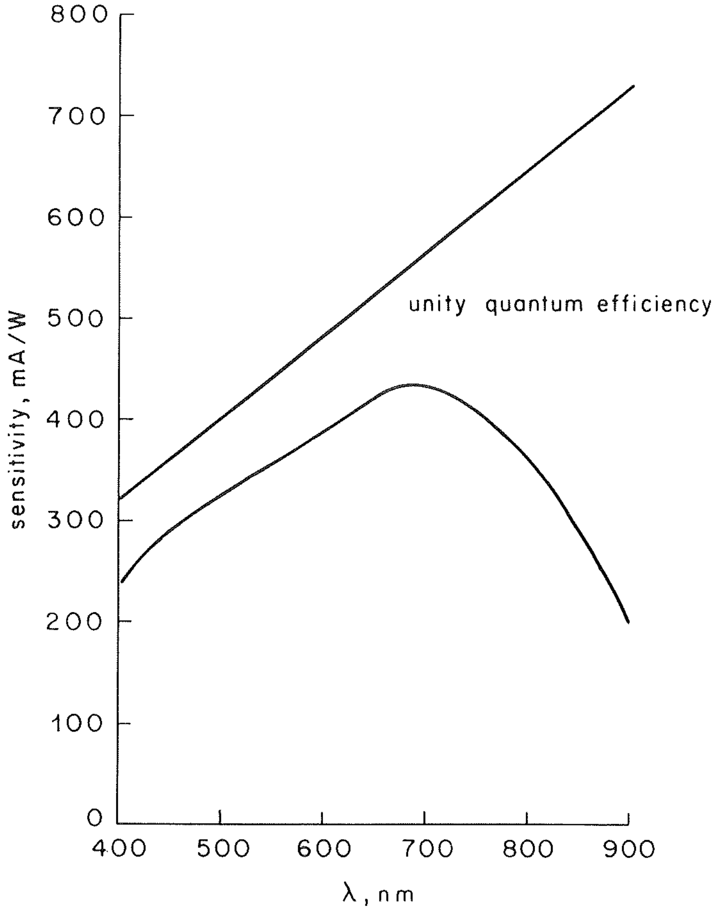

Fig. 9 - Typical spectral response of a silicon diode vidicon-type tube relative to 100% quantum efficiency

4. Experimental investigations

4.1. Clocking speed, transfer efficiency, charge bias

4.1.1. Attainment of maximum clocking speed with optimum charge bias

In this investigation the clocking speed of the device was increased up to the value at which the transfer inefficiency became unacceptably high, even when using charge bias. In this part of the investigation the device was used as an analogue shift register.

A conventional video signal was introduced together with a bias component. The video level was 0·3v pp and the bias could be varied over the range 0 to 10v. The output signal was viewed on a picture monitor and the clock frequency was gradually increased; thus a continual qualitative check on the frequency characteristics of the signals was possible. At each new frequency, the charge bias was adjusted for optimum results.

It was found possible to increase the clock frequency to 11 MHz before serious loss of resolution became apparent. At this frequency, the shape of the clock pulses was very critical indeed, and is illustrated in Fig. 10.

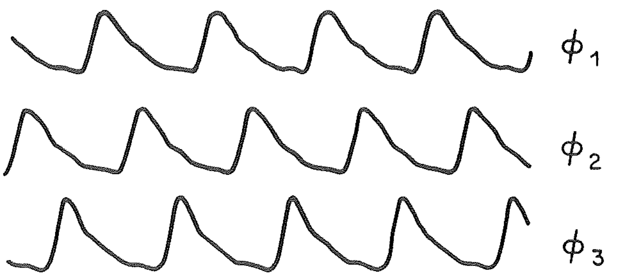

Fig. 10 - Actual shape of 3 phase clocking waveforms at 11 MHz

Any attempt to reduce the fall times of any of the three pulse trains resulted in an immediate increase in transfer inefficiency, and it seems reasonable to conclude that this value of fall time, roughly 40 ns, represented the minimum carrier transfer time within the device, even with charge bias. The deviation of the clock waveforms from the ideal shape already shown in Fig. 1 was difficult to avoid since the impedance of a CCD clock drive input is almost entirely capacitive and comparatively large clock signals at high speeds are involved.

4.1.2. Transfer efficiency measurement

Having achieved the highest possible clocking frequency, an objective measurement of the amplitude/frequency characteristic of the CCD could be carried out using a spectrum analyser. The response so obtained is plotted in Fig. 11 for five nominally identical CCD's*. In each case, the charge bias was adjusted to give optimum response at high frequencies. There was a very large difference between the best and the worse performances, one device in particular had an extremely poor characteristic. Since the clocking frequency was 11 MHz, the maximum permissible input frequency was 5·5 MHz.

The curves in Fig. 11 were used to calculate the transfer efficiency using the expression already discussed:

$$A_o = A_i \ \text{Exp}\ (-n\epsilon\ [\ 1 - \text{Cos}\ 2\pi f/f_c\,]\ ) \qquad (2)$$

$\text{Log}_e\ (A_o/A_i)$ was plotted as a function of $(1 - \text{Cos}\ 2\pi\ f/f_c)$. The slopes of the resulting lines thus yielded $- n\epsilon$.

The values of transfer efficiency so obtained are shown in Fig. 11 for each device. The results illustrate the wide range of performances resulting from relatively small changes in transfer efficiency, and underline the point made in section 3.1. about the cumulative effect of transfer inefficiency in a long array.

An alternative approach to the measurement of transfer efficiency was also attempted; this consisted of monitoring the pulse response obtained when a single pulse with a duration of one clock period was introduced into the input diode of the CCD. Fig. 12 illustrates the pulse response after 100 elements, obtained from the array with the best performance. The relative pulse level of each output sample is plotted for a number of charge bias voltages, and it can readily be seen that there is an optimum charge bias necessary to achieve the least amount of charge smear. At low levels of charge bias injection the smearing is due to the effects of transfer inefficiency, at high levels of charge injection it is due to limiting, the charge handling capacity of the CCD having been exceeded.

At best, the relative output level was 0·825, and from the curve in Fig. 6 it can be deduced that this roughly corresponds to a transfer efficiency of 0.9993. This is in fair agreement with the results obtained previously using the measured amplitude/frequency characteristic.

4.2. Linearity

Since CCD charge transfer is conceptually a linear process, the light input/signal output characteristic of a CCD sensor should also be linear. Observations during the course of the experimental work, however, did not substantiate this. Measurements were made of the output signal as a function of light intensity, using a clock frequency of 10 MHz. The relationship so obtained is plotted in Fig. 13. It is clearly not linear, and appears to approximate to a power law. It was decided to repeat the experiment at the lower clocking rate of 1·7 MHz, as

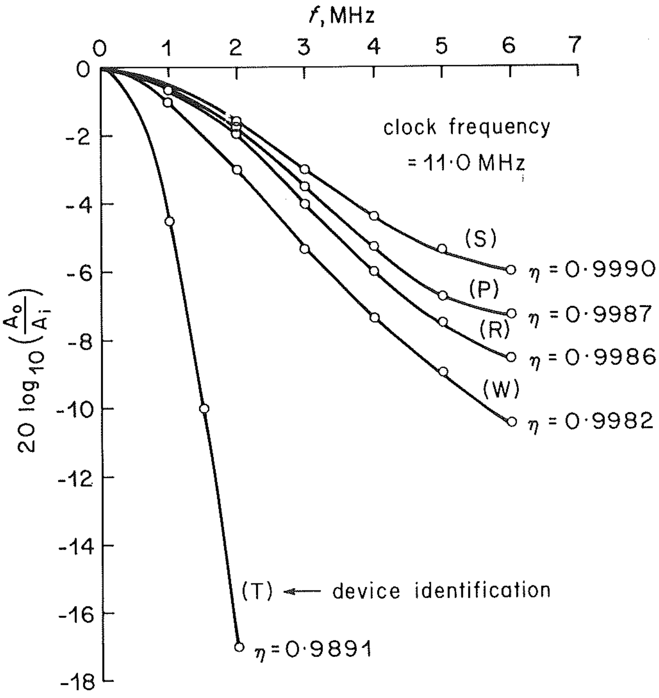

Fig. 11 - Frequency response of the CCD's when used as analogue shift registers with 11 MHz data rate

this was virtually the lowest frequency which could be used consistent with the complete clocking out of all the information within approximately 64 μs (the duration of a television line period.

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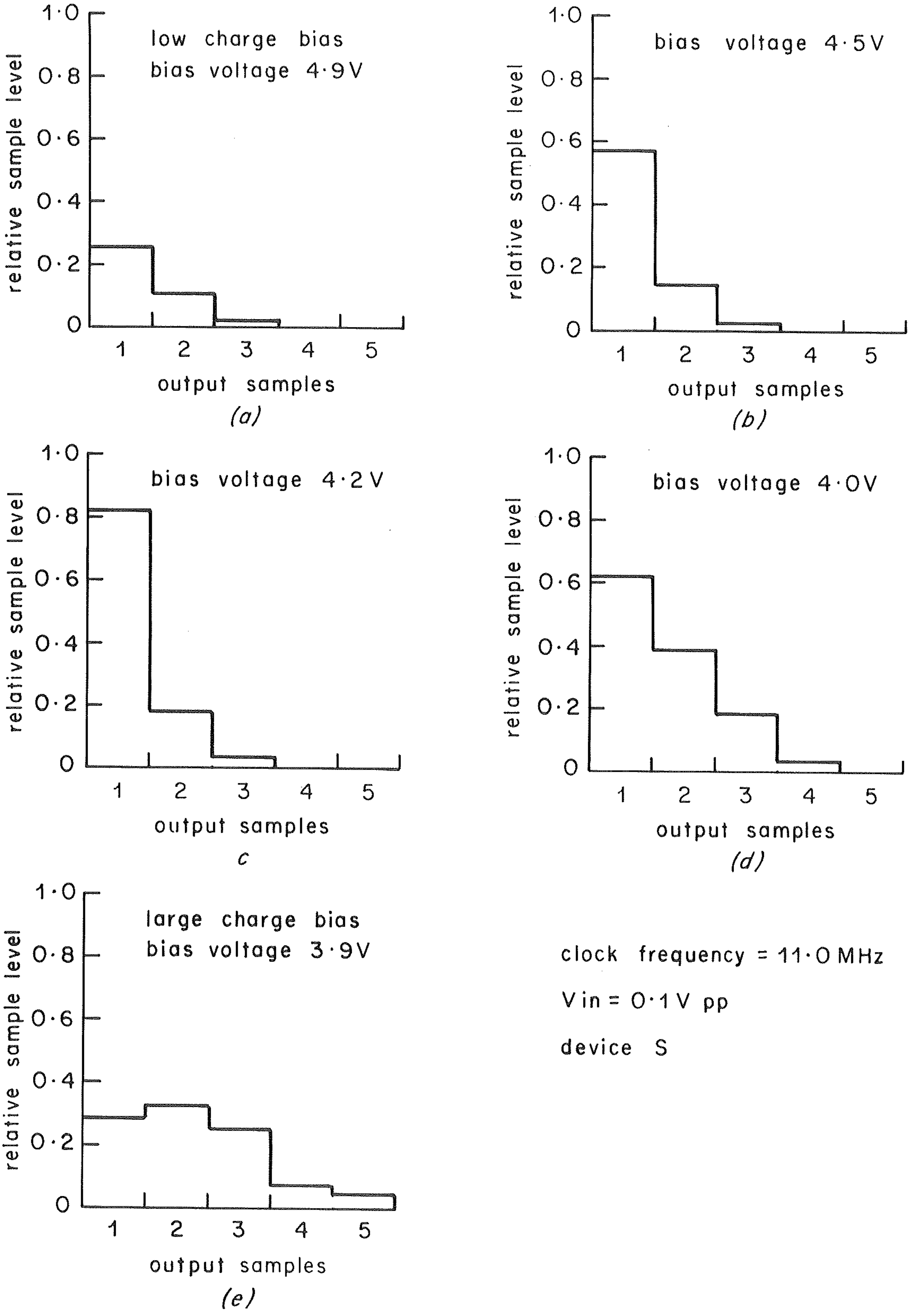
* On this diagram, and throughout this report individual CCD's are identified by a consistent code letter. The appendix at the end of this report contains a key to the manufacturers own serial numbers which are of little interest to the general reader, but enable devices to be identified by their manufacturing batch and slice numbers. These are of particular significance in section 4.6.

The curve so obtained was markedly different from that obtained at 10 MHz. It was approximately linear over most of the range, although not so at low signal levels.

Since the device has an inherently linear light intensity charge production characteristic, the explanation



clock frequency = 11·0 MHz

Vin = 0·1 V pp

device S

Fig. 12 - Pulse response of the CCD for various charge bias levels

of the cause of this effect can be sought in the on-chip output circuit of the particular device in question which was not designed to operate at 10 MHz.

4.3. Sensitivity variations

Sensitivity variations were observed in all the devices tested. They were observed in uniform illumination at roughly 75% of saturation level. The variations could then be seen by viewing the output signal on an oscilloscope.

Tests were originally made using tungsten light with an infra-red filter cutting off at approximately 750 nm. Fig. 14 shows the results obtained. For comparison, the tests were carried out using two different clocking rates, 10 MHz and 1·7 MHz. Whilst the sensitivity variations given by one particular device differred somewhat for the two clocking speeds, these differences were mainly confined to short-term variations. These were generally greater with the 1·7 MHz clocking rate, which points to a somewhat better transfer efficiency at this frequency.

The long-term and short-term variations were esti-

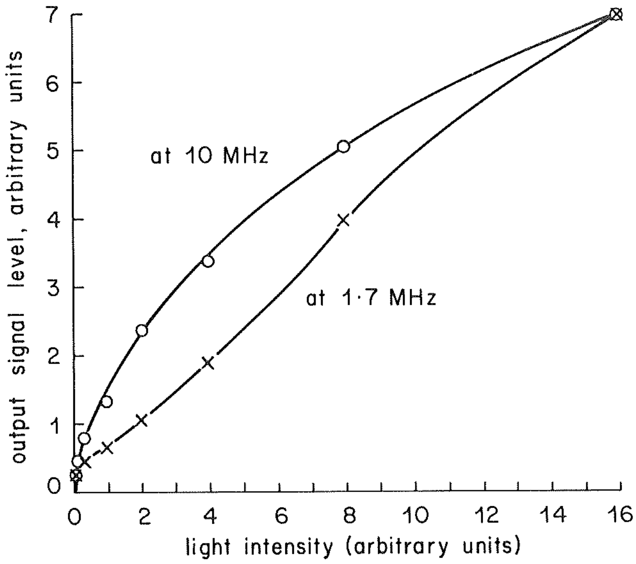
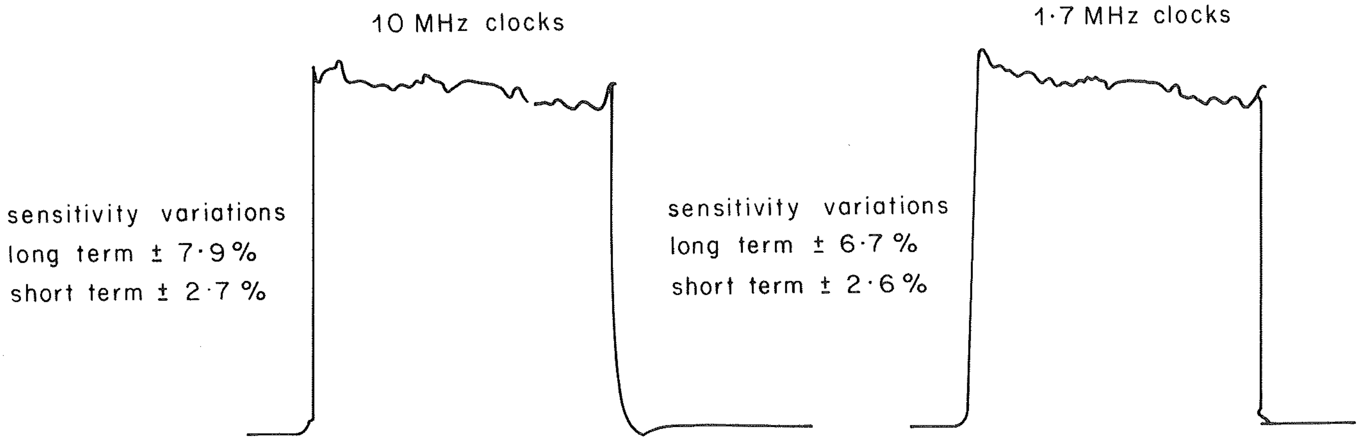
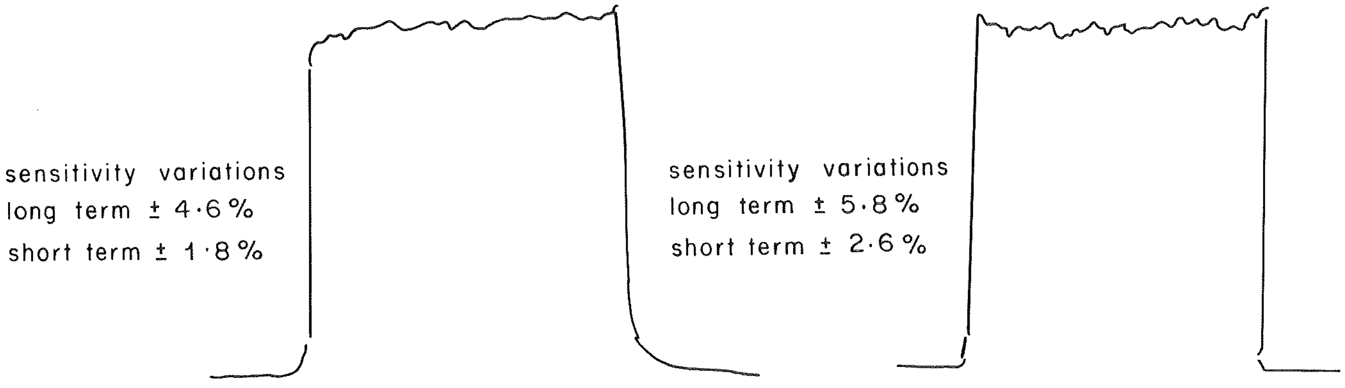


Fig. 13 - Linearity of the CCD at 10 MHz and 1·7 MHz data rates



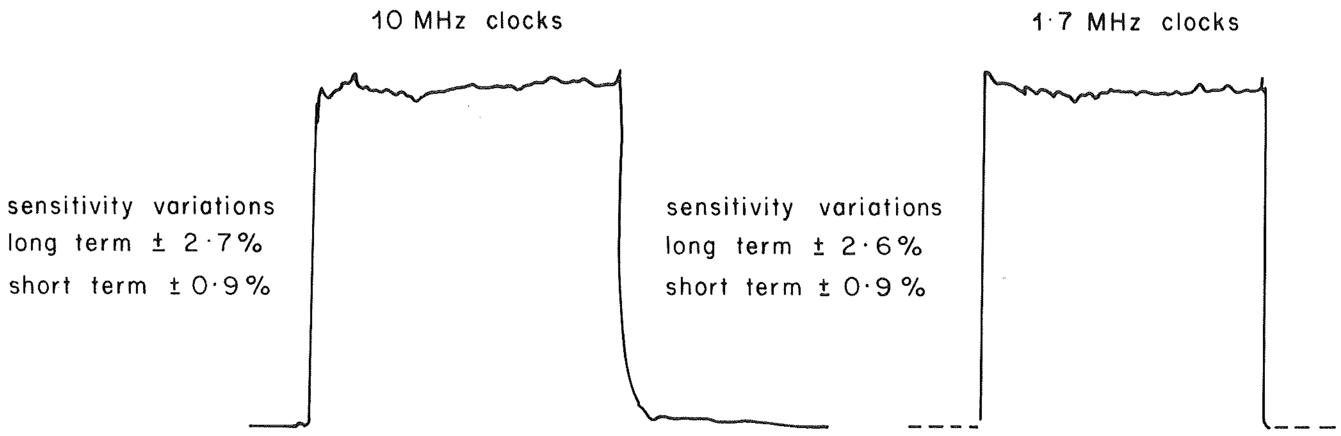
(a) CCD device R



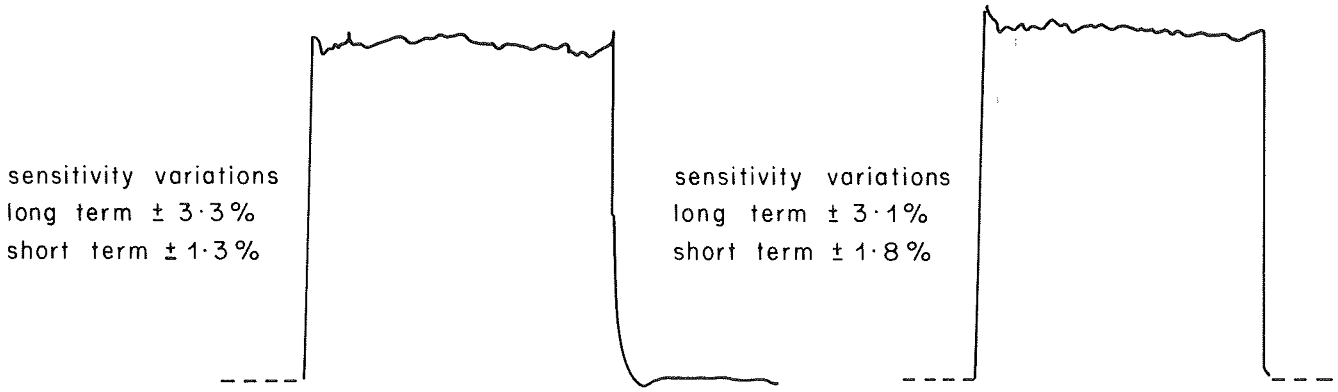
(b) CCD device S

Fig. 14 - Sensitivity variations at 10 MHz and 1·7 MHz data rates

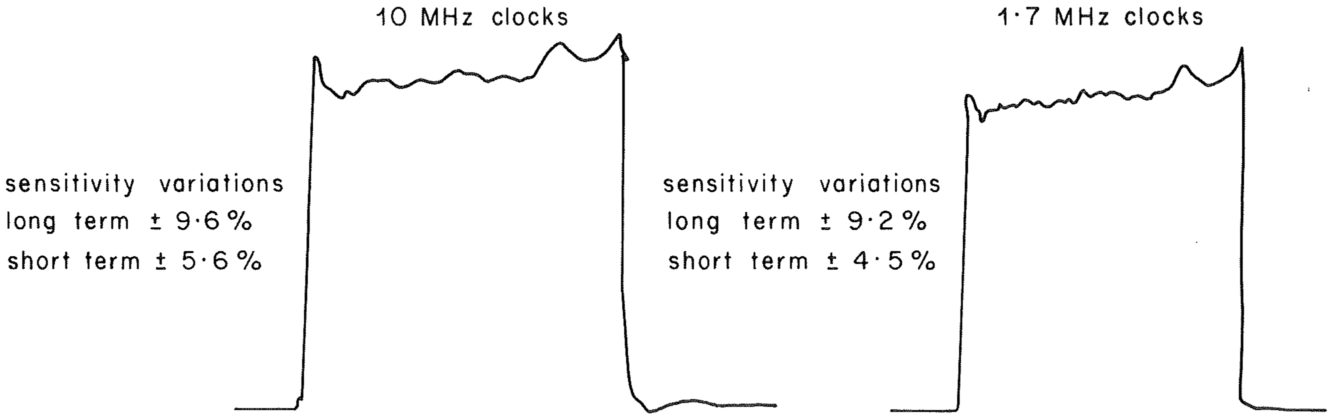
14(a) Device R   14(b) Device S



(c) CCD device P



(d) CCD device Q



(e) CCD device T

Fig. 14 - Sensitivity variations at 10 MHz and 1·7 MHz data rates

14(c) Device P 14(d) Device Q
14(e) Device T

mated in each case, short-term variations were, for the purpose of this work, regarded as those occurring within approximately five samples. (The individual samples are not shown, the output signals having been filtered with a cut off frequency slightly less than half the clocking frequency).

In television image-sensing applications, short-term variations are the most obvious, and thus the most damaging. For the devices tested, they were somewhat smaller than expected being typically in the range 0 to ± 3%. One device, however, showed a poor performance Fig. 14(e); this is the device with the rather poor transfer efficiency illustrated in Fig. 11.

It was decided to try and detect any differences in the sensitivity variations as a function of light wavelength. For this work, the tungsten light source was filtered by each of four filters having the characteristics shown in Fig. 15, and corresponding to Red, Green, Blue and Infra-red.

The sensitivity variations for each colour are shown in Figs. 16 and 17 for two of the CCD's. These devices were selected from those previously observed as having the most non-uniform and the most uniform sensitivities respectively. In Fig. 17, the differences between the responses to different colours are small, although largest between infra-red and any of the others. In Fig. 16 however, the differences are very large, there being local variations of as much as 20% between the responses to the red/infra-red end of the spectrum and the green/blue part of the spectrum. This is thought to be due to local variations in the silicon which affect carrier life-time. Carriers generated by long wavelength radiation are generated deeper in the substrate than those produced by shorter wavelength radiation. Before contributing to the signal, they must travel further to the surface, and in so doing

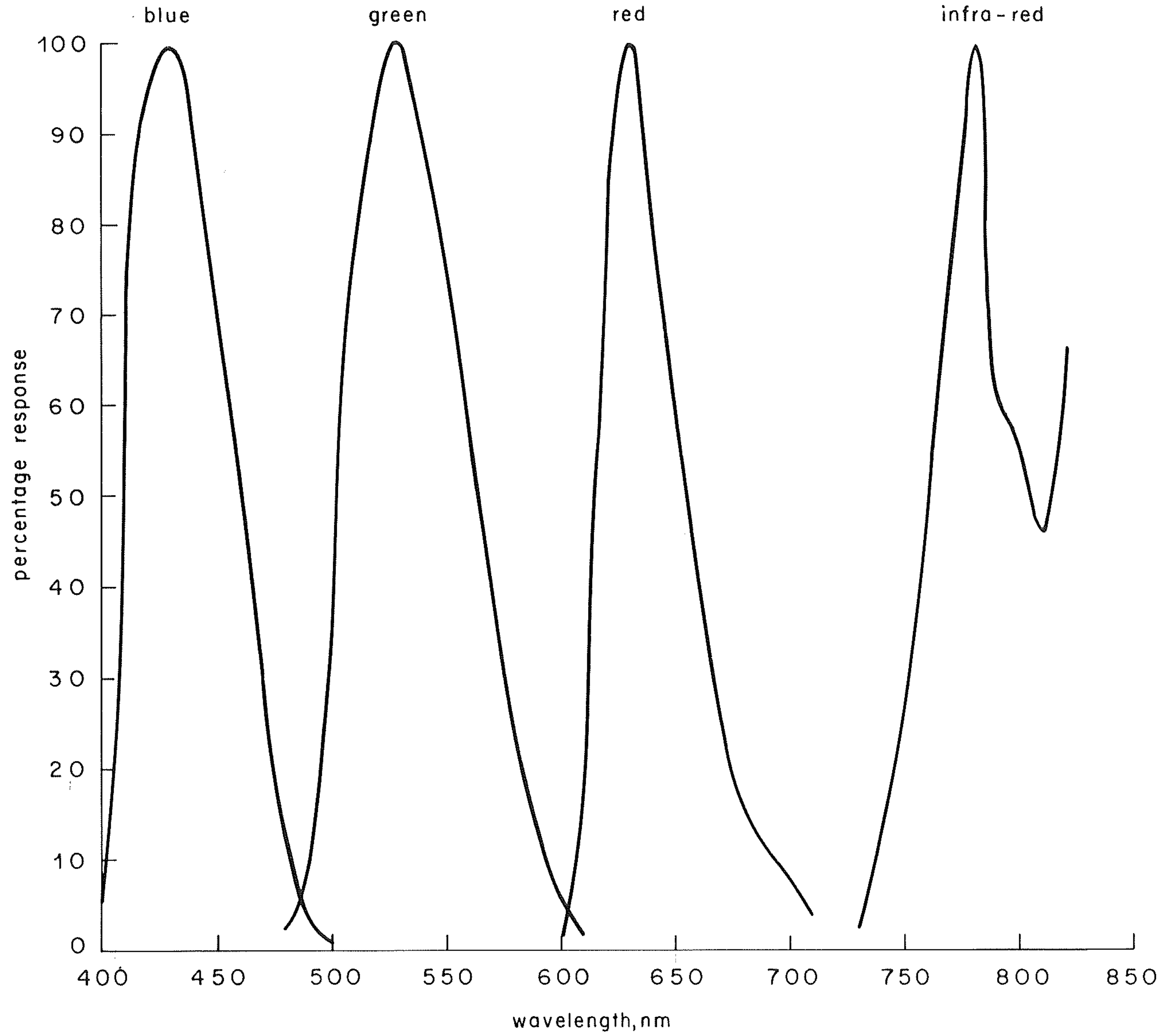


Fig. 15 - Spectral responses of the filters used to produce R,G,B, and Infra-red sources

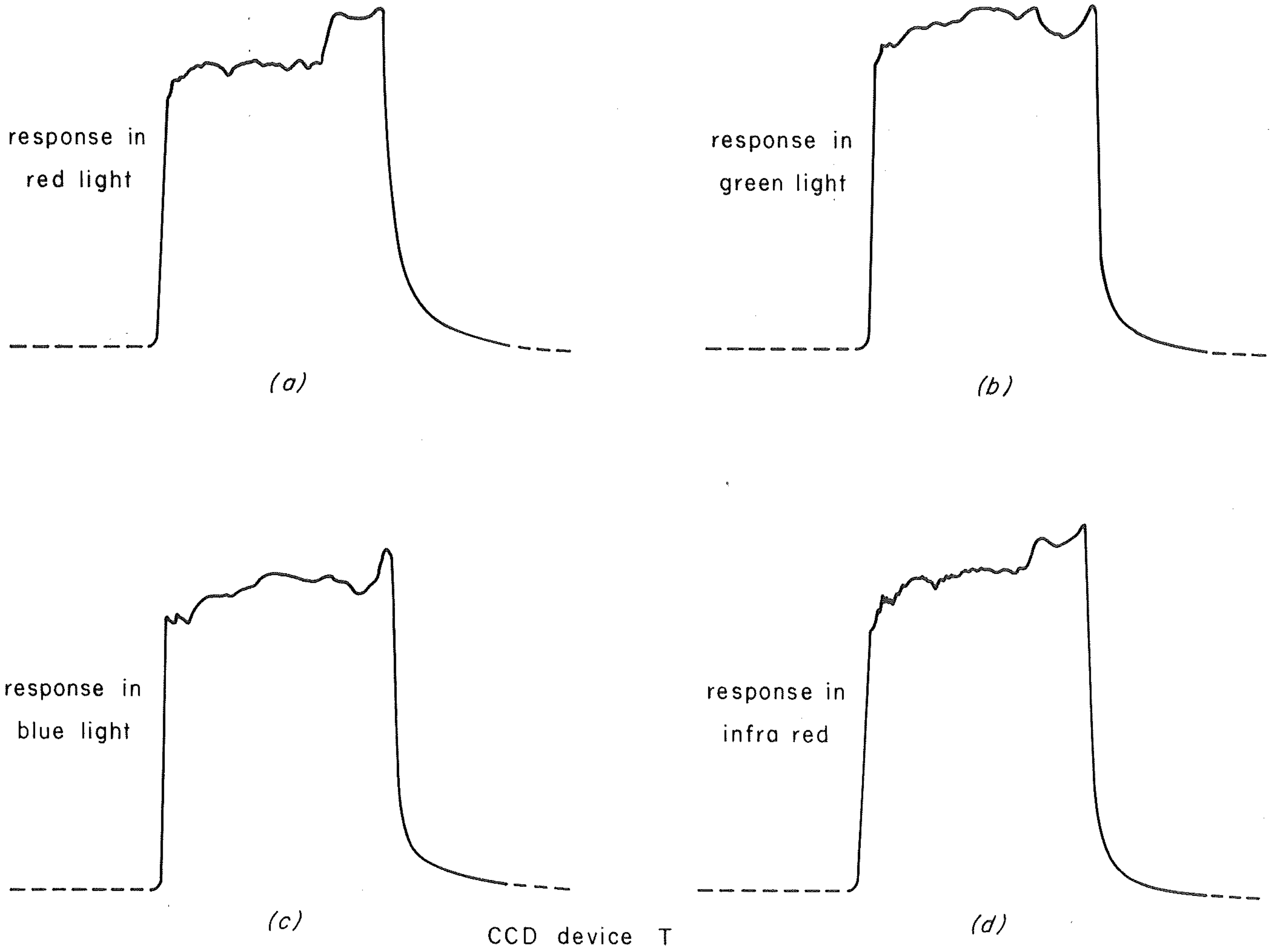


Fig. 16 - Sensitivity variations in device T

16(a) In Red 16(b) In Green 16(c) In Blue 16(d) In Infra-red

are more susceptible to losses due to recombination.

4.4. Image formation

The number of light sensitive elements in each device (97) was not sufficient to produce a television image of satisfactory resolution. It was decided that the most valuable assessment of imaging performance would be provided by regarding each image sensor as part of a high resolution device. Accordingly, using a clock frequency of 10 MHz, the image size was adjusted such as to provide a strip of picture roughly $^1/_5$ of the image area, corresponding to a high resolution device having a potential resolution of 5 MHz over this area. The images were obtained from film using the self-scanning of the array to provide horizontal scanning and the film was moved continuously at 50 frames/second to provide vertical scanning.

Fig. 18 is typical of the images so obtained; it illustrates clearly that fair resolution is possible at this clock frequency, although it must be noted that both horizontal and vertical aperture corrections were applied. The apparent resolution at 5·5 MHz is caused by an alias component equal to the difference frequency (10 – 5·5) MHz = 4·5 MHz.

The results shown in Fig. 18 were obtained without the use of any intentional charge bias, but judging from the high resolution obtained, the transfer efficiency must have been relatively high. This apparent contradiction can be explained if it is realised that only a comparatively small amount of charge is required to fill the surface states. This means that charge trapping becomes relatively insignificant in the presence of large input signals, and this effectively increases the transfer efficiency. Furthermore, in the application being considered it is likely that the optical flare will have been sufficient to provide the necessary degree of charge bias. This explanation is supported by Fig. 19 which shows the effect of reducing the light level by approximately 80% and increasing the subsequent gain in order to compensate. The impairment of resolution due to the reduction in transfer efficiency is very apparent, and this is explained by the very much lower level of signal and flare.

It should be noted, however, that in the image-sensing mode, impairment of resolution due to transfer inefficiency is not uniform along the television line. The effect of transfer inefficiency is clearly most damaging to those parts of the signal that have undergone the greatest number of transfers. In a CCD sensor used for television image-sensing, the resolution should vary across the television line, being worst on the right hand side, and best on the left hand side of the picture. This is illustrated by Fig. 20 which was taken under the same lighting conditions as Fig. 19 but with the resolution bars moved to test the spacial frequency characteristic on the left of the picture. The difference in resolution between Fig. 19 and Fig. 20 is clear. There is even some evidence of a left-to-right variation in the characteristic across the width of the frequency bars in Fig. 20.

It is important to realise that the apparently good results shown in Fig. 18 can be misleading; even if CCD sensors were made with an adequate number of elements for television line scanning (600 or so) using the surface channel technology exemplified by the devices tested, the loss of resolution from left to right would be of the order of 36 db. This is clearly unsatisfactory since it virtually rules out their use in such applications. Buried channel or Peristaltic* technology appears to offer the only hope of producing CCD sensors with the necessary properties for this type of application.

4.5. Measurement of dark current variations

One of the most objectionable impairments seen on CCD array-derived pictures is caused by irregularities in the dark current generated by the device. They can clearly be seen as white blemishes in virtually all the published photographs of pictures produced by CCD's. In the mode in which the present devices were being used, dark current variations were not readily seen. This is because the integration time for each exposure was very

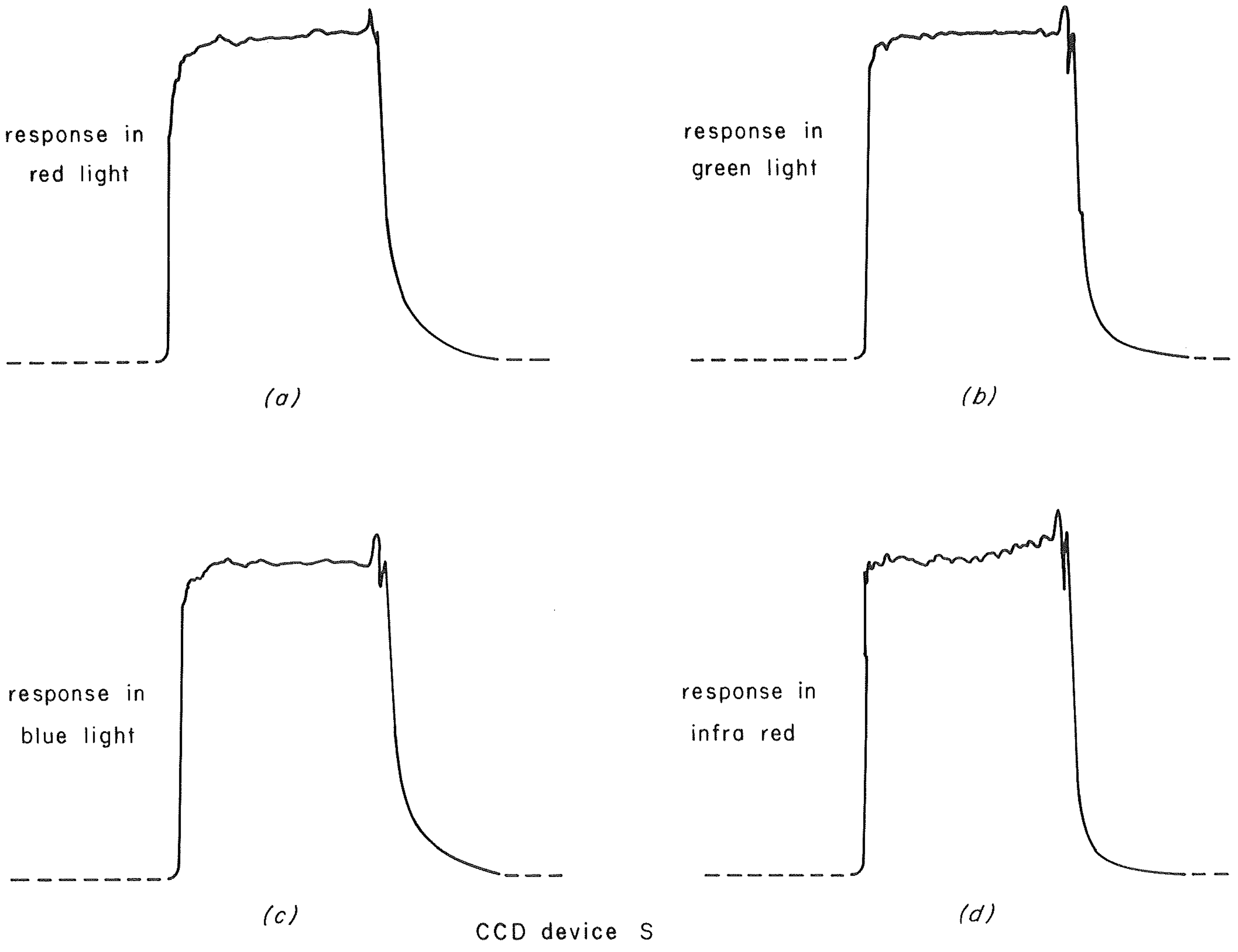


Fig. 17 - Sensitivity variations in device S

17(a) In Red 17(b) In Green 17(c) In Blue 17(d) In Infra-red

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* A form of Buried Channel technology developed by Philips.

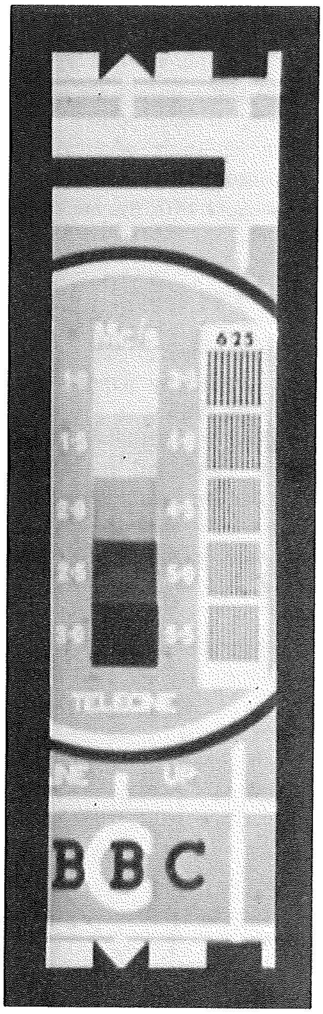

Fig. 18 - Image formation at 10 MHz data rate at near-saturation level

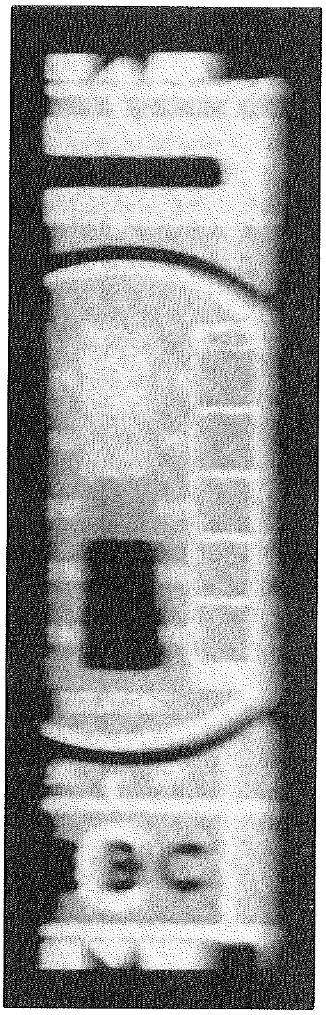

Fig. 19 - Image formation at 10 MHz data rate using only 20% of the light

short (only about 60 μs) and the light level was adequate to give exposures just short of saturation. In pictures produced from an area array on the other hand, the integration time is either one television field, or one television picture, depending on the scanning organisation used.

In order to observe and measure dark current 'spikes', the integration time was increased by a factor of 1024. One device thereupon revealed three large spikes of levels 17%, 11% and 4% of saturation, see Fig. 21. This was, however, the only device on which such impairments were seen.

At the integration times suitable for television image formation, these spikes would have been ·017%, ·011% and ·004% respectively. After gamma correction the largest spike would then be approximately 1·3% of white signal, at worst, and this might just be perceptible. This however represents the worst case seen and it may well be unnecessary to carry out any correction for dark current variations if CCD sensors ever find application in telecine applications using one dimensional line scanners; the integration time would be one television line period, and the available illumination would be relatively unrestricted.

4.6. Spectral response

Using a variable wavelength light source of calibrated intensity (monochromator), the spectral response of each device was measured and plotted over a wavelength range from approximately 400–900 nm, thus covering the visible region from blue through to infra-red.

The results so obtained are plotted in Fig. 22 (a) to (g) inclusive. Although all the CCD sensors tested were nominally identical, the spectral responses were not. The principal feature common to all the responses is the fine structure, due to the multilayer form of construction. There are certain similarities in the fine structures which enable them to be grouped into three groups. For example, similar features are to be found in devices P and V, in Q, S and U, and in R and T. The manufacturers have been able to confirm that these three groups correlate with the batches from which they came.

The trend in all the devices is for the response to fall off sharply with decreasing wavelength at approximately 450 nm and this confirms the expected poor blue response. It is worth noting, however, that device U has a relatively high response (32%) at 450 nm and a significant response (15%) at 400 nm. This appears to be due to the fortuitous presence of an interference peak in this region.

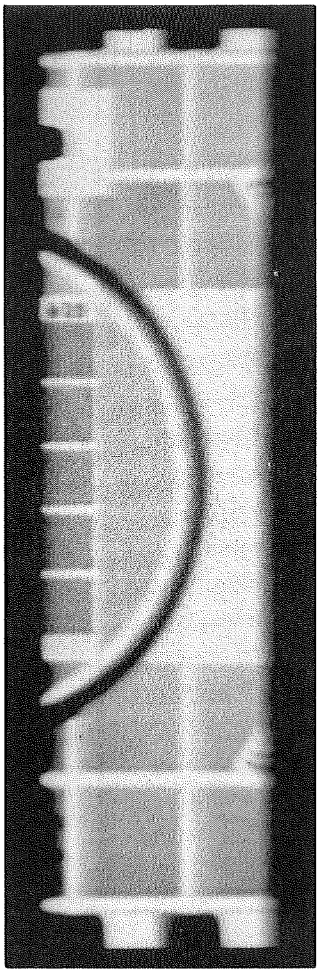

Fig. 20 - Lighting as for Fig. 19, but showing improvement in resolution on left hand side of picture

Although not strictly relevant to this investigation it is interesting to compare the responses of the CCD sensors with those of two silicon diode arrays which were measured by the same technique. These are illustrated in Fig. 22(h). The arrays were made by different manufacturers but to similar specifications. The absence of large interference peaks is evident from the two curves as is the somewhat better response in the blue. These features are not surprising since the image falls directly upon the silicon diodes with no intervening multiple layers, and no polysilicon. These curves probably represent the type of response which could be achieved using a device with back imaging.

5. Conclusions

The investigation just described has served the valuable purpose of providing first-hand laboratory experience in the operating and testing of CCD sensors, and has provided information that could be used in drawing up a realistic target specification for devices intended as image sensors in broadcast applications.

An important conclusion to be drawn from the work is that if the devices tested are representative of surface-channel technology with charge bias, then it probably cannot provide sufficient operating speed to be usable at 625 line television scanning rates. In order to provide solid state image-sensors of comparable quality to existing camera tubes, many further improvements will be necessary.

It will, for example, be essential to mitigate the effects of blooming which, in a one dimensional array, is seen as a horizontal streaking of the picture on highlights and, in a two dimensional array, will be seen as vertical and horizontal streaking.

The spectral response at the blue end of the spectrum will need to be improved, perhaps by back imaging, and the spectral response will have to be consistent between devices of the same type.

Dark current blemishes will probably remain a problem with area arrays for a long time, although their severity may be eventually reduced by on-chip cooling; in the meantime, sophisticated techniques for mitigating the effects electronically will probably be desirable. In applications where a linear array can be used, such as film scanning, the yield of blemish-free devices may be sufficiently high to make such correction unnecessary; further, the integration times in such applications are sufficiently short to make dark current blemishes relatively unimportant.

Non-uniformity of sensitivity over the array is another effect for which electronic correction might have to be considered. In spite of the comparatively low level of these variations (± 3% on the samples tested), they can usually be seen on the output signal, for example, careful examination of Fig. 18 will reveal them as vertical

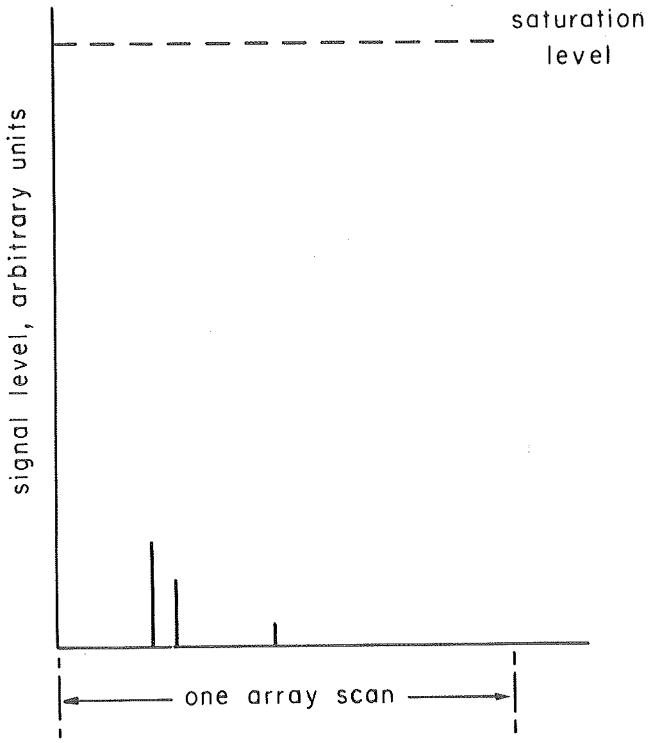

Fig. 21 - Level of dark current blemishes observed on one device

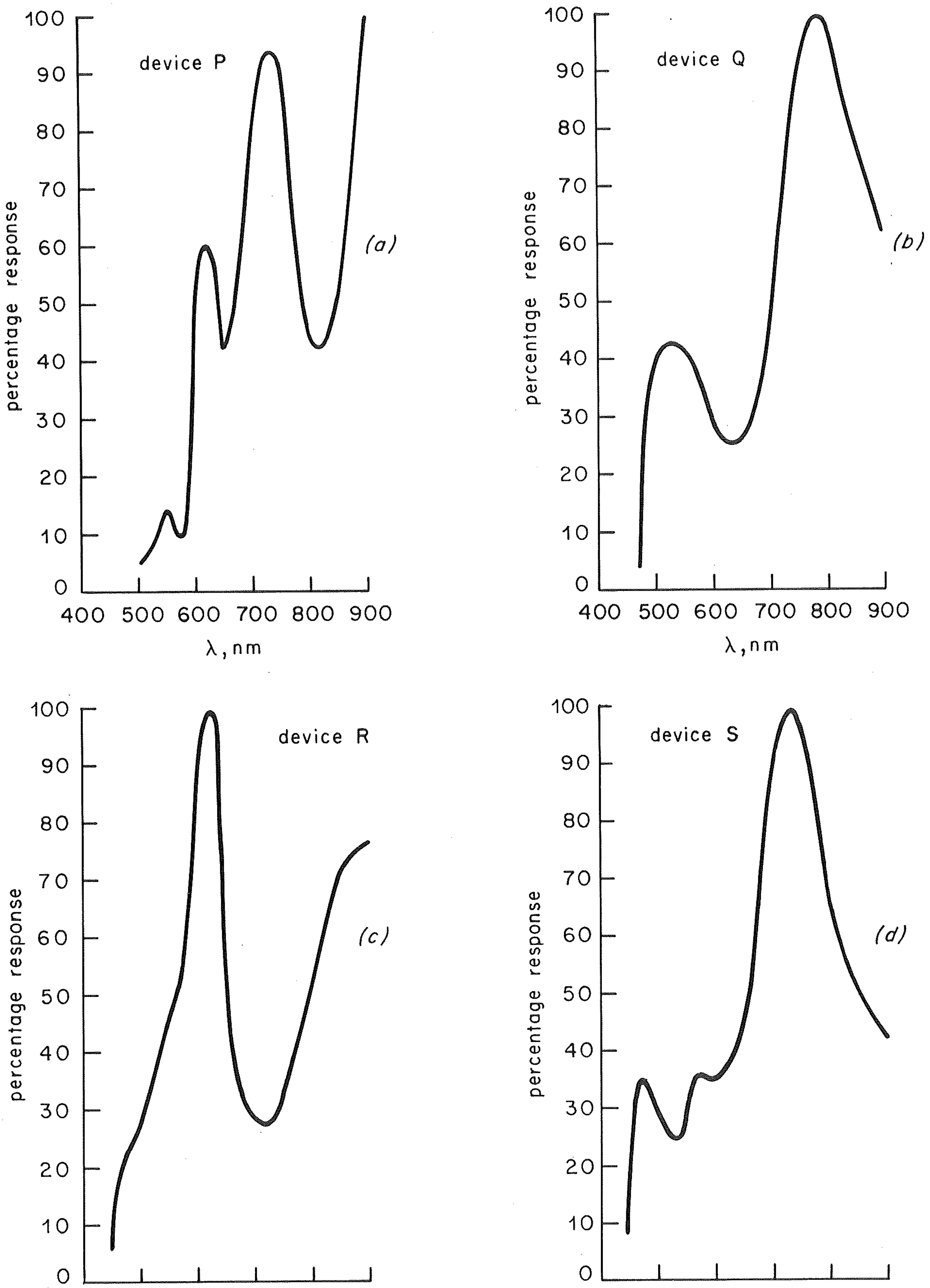

Fig. 22 - Selection of spectral responses of the CCD's and, for comparison, two photodiode arrays

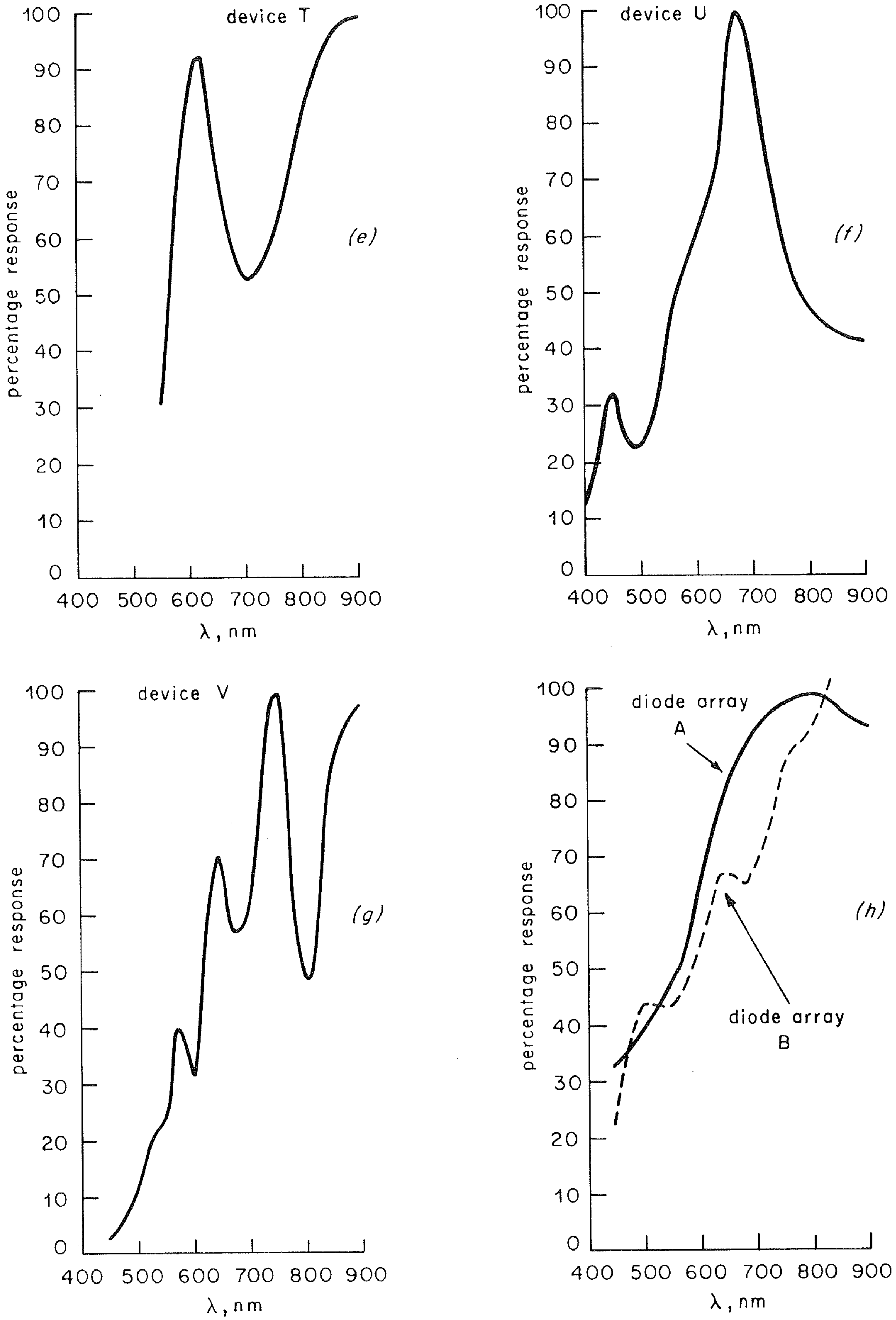

Fig. 22 - Selection of spectral responses of the CCD's and, for comparison, two photodiode arrays

striations. They will always appear as vertical striations in the pictures derived from linear arrays, and this is particularly objectionable.

Work is already proceeding to develop methods for electronically correcting sensitivity variations and dark current blemishes. At this stage, the techniques being developed appear to be feasible, although the electronic storage is relatively costly at the present time. The viability of these correction techniques will therefore depend upon the future availability of cheap high-capacity data stores, perhaps based upon CCD's.

6. Acknowledgements

Thanks are due to Mr. D.J. Burt and his colleagues at GEC Hirst Research Centre, Wembly, for supplying the CCD's for testing, and for taking a continuing interest in the project.

7. References

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APPENDIX

Identification of the CCD's used in the tests

P = Device no. 881-18

Q = Device no. 899-38

R = Device no. 899-16

S = Device no. 899-10

T = Device no. 899-3

U = Device no. 881-23

W = Device no. 881-27

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